

Stellar Subsystems of the Galaxy NGC 2366.

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Abstract. Hubble Space Telescope archive data are used to perform photometry of stars in seven fields at the center and periphery of the galaxy NGC 2366. The variation of the number density of stars of various ages with galactocentric radius and along the minor axis of the galaxy are determined. The boundaries of the thin and thick disks of the galaxy are found. The inferred sizes of the subsystems of NGC 2366 ($Z_{thin} = 4$ kpc and $Z_{thick} = 8$ kpc for the thin and thick disks, respectively) are more typical for spiral galaxies. Evidence for a stellar halo is found at the periphery of NGC 2366 beyond the thick disk of the galaxy.

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INTRODUCTION

Studies of the stellar populations in irregular galaxies have shown that young stars, and, to a lesser extent, old stars, are concentrated toward the center, with old stars extending to much greater galactocentric distances than blue stars [1—6]. The number densities of old stars in individual galaxies decrease exponentially with galactocentric radius [6—9]. Based on an analysis of the space distribution of stars of various ages in nine spiral and 24 irregular galaxies, we proposed empirical models

of the structure of the distribution of stars in spiral and irregular galaxies [9, 10], which reflect the characteristics of the distributions of stars of various ages. The resulting models for the distributions of stars in spiral and irregular galaxies are similar, and differ mostly in the spatial sizes of stellar subsystems and the presence a stellar halo in massive spiral galaxies.

Intermediate-type galaxies (between irregulars and spirals) fell beyond the scope of our previous studies. Such galaxies are most often represented by massive irregulars or late-type dwarf spirals with inconspicuous arms. However, studies of intermediate-type galaxies are important in connection with the question of why spiral, but not irregular, galaxies have halos. Studies of individual galaxies suggest that there must be some relation between the mass of a galaxy and the presence or absence of a halo at its periphery. Some massive irregulars (IC 10, M 82) have conspicuous halos [9, 11], whereas no halos have been found in some dwarf spirals. Revealing the origins of halos requires increasing the number of transition-type galaxies studied.

NGC 2366 is of special interest among intermediate-type stellar systems. A fairly large number of images taken in various fields across the periphery of the galaxy are available from the Hubble Space Telescope (HST) archive (Fig. 1). NGC 2366 is usually classified as an irregular (NED), although Baade [12] considered it to be a low-luminosity spiral galaxy. NGC 2366 belongs to the M81 group (Table 1), and is mostly interesting because of the giant star-forming region NGC 2363 at its periphery. The stellar population of the central regions has been studied in detail by a number of authors [14–17], but no studies of the stellar populations at the galaxy periphery have been made previously.

The $UBVJHK$ and H_α images of NGC 2366 show a stellar disk with a well-defined oval shape [18], which is viewed at an angle of nearly 90° , whose brightness decreases exponentially from the center toward the edge. The observed asymmetric distribution of young stars along the major axis of the galaxy is due to star-forming regions. Star formation is especially violent in the region of the giant $H II$ complex NGC 2363, but, on the whole, the star-formation rate in NGC 2366 does not appreciably exceed the average rates in other galaxies of the same type [18].

The outer structures of the galaxy are conspicuous in the HI map, where we can see two extended branches aligned parallel to the major axis of the galaxy [18]. The behavior of the azimuthally averaged HI surface density in NGC 2366

resembles the behavior of the HI surface density in other irregular galaxies, except for the outer parts of NGC 2366, where the HI density decreases more slowly and emitting regions extend farther from the center [18]. The outer boundary of the HI distribution agrees approximately with the outer parts of the optical image, but is asymmetric with respect to the V isophote. Richer and Sancisi [19] point out that this is a common feature in disk galaxies.

STELLAR PHOTOMETRY

We consider here images adopted from the HST archive (Table 2), and used the MIDAS DAOPHOT II [20] and HSTphot [21, 22] programs to perform stellar photometry. We calculated the completeness of the sample of stars identified using the standard method of artificial stars, adding several hundred artificial stars of various luminosities to the sample. The accuracy of the photometric zero point in HSTphot is about 0.05^m [22], and this determines the photometry accuracy for all bright stars. We use the recommendations of Holtzmann et al. [23, 24] when transforming the instrumental DAOPHOT II magnitudes into the standard Kron-Cousins VI system.

DAOPHOT II and HSTphot photometry yield virtually identical results for bright stars in HST images. However, HSTphot photometry is more accurate internally for faint stars, as is evident from the decrease in the width of the red-giant branch obtained using the different programs applied to stars in the same field. This increase in the internal accuracy is most likely due to the use of stricter star selection criteria in the final photometric list, and the more refined technique used to estimate the sky background in the vicinity of the stars measured. However, DAOPHOT II photometry has deeper limiting magnitude and can be used for images taken in a single filter, when HSTphot cannot be applied.

RESULTS OF STELLAR PHOTOMETRY

Figure 2 shows the results of our photometry for stars in NGC 2366 in the form of color—magnitude (CM) diagrams. The diagrams for the central regions of the galaxy (fields SI and S2) do not differ from those of starburst galaxies. We can see branches populated by (1) young stars — blue and red super-giants; (2) intermediate-age stars — the asymptotic giant branch (AGB), and (3) old stars — the red-giant branch

(RGB). The CM diagrams for fields located at large galactocentric distances (S3, S4, S6, S7) show only RGB stars, with few AGB stars.

The distance of NGC 2366 has been determined using various methods (Table 3). The populated red-giant branch, which is conspicuous in the CM-diagrams (Fig. 2), can be used to find the distance via the Tip of the Red-Giant Branch (TRGB) method [28], which was used to by Thuan et al. [26] and Karachentsev et al. [27]. Both teams based their estimates on only a single field, whereas we have used images of four fields. The tips of the red-giant branches of fields SI, S2, S3, and S4 were determined by applying a Sobel filter to the corresponding luminosity functions (see [29]). We took the halfwidth of the Sobel filter to be the uncertainty of the tip of the red-giant branch. Abrupt changes in the slopes of the luminosity functions of fields SI, S2, S3, and S4 in Fig. 3 corresponding to the tip of the red-giant branch are visible at $I = 23.56^m, 23.50^m, 23.55^m$, and 23.55^m . The average value is $I_{TRGB} = 23.54^m \pm 0.04^m$. The extinction toward NGC 2366 is $A_V = 0.12^m$ [13]. We used the equations of Lee et al. [28] to infer the distance modulus $m - M = 27.48^m \pm 0.17^m$, corresponding to a distance of $D = 3.13 \pm 0.25$ Mpc. The Final distance uncertainty includes the uncertainties in the TRGB method (0.10^m), the TRGB magnitude (0.04^m), and the HSTphot method (0.05^m). The distance error also includes the error of the red-giant photometry, since this leads to some scatter of the stars in the CM diagram and broadens the Sobel function. The average accuracy of the WFPC2 (HST) photometry of a single star is 0.06^m at $I = 23.5^m$, but the accuracy of our result is increased by our use of more than a dozen stars at the red-giant boundary to calculate the tip of the red-giant branch.

Our distance estimate for NGC 2366 agrees with that of Karachentsev et al. [27], but not with the value obtained by Thuan and Izotov [26]. This discrepancy must be due to the use of different calibration methods. Our photometry yields low metallicities for red giants, $[Fe/H] = -1.96$, consistent with the low metallicity of the galaxy determined earlier using spectroscopic methods.

DISTRIBUTION OF STELLAR NUMBER DENSITY AND THE SIZES OF THE STELLAR SUBSYSTEMS.

We chose two directions to study the visible distributions of stars across the body of the galaxy: perpendicular to the equatorial plane of the galaxy (along the Z axis) and in the radial direction, from the center of the galaxy outward. Our choice of this

latter, not very convenient, direction is due to the orientation of the images taken with the HST telescope.

We used our CM diagrams to select stars of various ages. Figure 2 (field S2) shows regions occupied by young stars — blue supergiants (BSG); intermediate-age stars — AGB stars; and old stars — red giants (RGB). We identify these domains in the CM diagrams for each field and use the stars falling within these domains to determine their number densities along the galactocentric radius and the Z axis. The only exception is field S7, for which deeper-exposure images are available. In this field, we were able to use fainter stars than in other fields of the galaxy to analyze the stellar number-density distributions.

Note that the AGB and RGB stars cannot be unambiguously distinguished at the upper boundary of the RGB, since the AGB also passes near the RGB, making it impossible to distinguish the two branches. The AGB stars affect the results only slightly, since they are scarce and their number does not exceed 10% of the total number of red giants. We therefore ignored this effect.

The boundary of the distribution of young stars, i.e., the boundary of the thin disk of NGC 2366, can easily be determined by analyzing the results for fields S3 and S4, which lie at this boundary. The number of blue stars in Figs. 4c and 4d decreases to zero at distances from the galactic plane of $Z = 1.5$ and 2.2 kpc, respectively. The AGB stars in these fields extend somewhat farther than the blue stars, but are less numerous, and fluctuations in their number density result in greater uncertainty in the inferred boundary of their distribution. The gradient of the number density of red giants in these fields is small, indicating the large extent of the old stellar subsystem.

A region with a high density of young stars can be seen in Fig. 4a at a galactocentric distance of 0.9 kpc against the overall decrease in the young-star number density with galactocentric distance. This region coincides with one of two hydrogen bridges extending parallel to the major axis of the galaxy. Hunter et al. [18] and Thuan et al. [30] interpret the extended hydrogen structures as an $H\text{I}$ ring tilted 60° to the line of sight. The overdensity of blue stars we have found in the region of this hypothetical ring (Fig. 4a) allows us to view the situation from a different angle. First, this extended stellar and gaseous structure may be associated with tidal interaction between NGC 2366 and its neighboring galaxies (e.g., with the nearby and more massive spiral galaxy NGC 2403). Second, it is possible that we do not

view NGC 2366 at an angle of 90° , and that the extended stellar and gaseous formations noted above are simply the spiral arms of NGC 2366. Other such galaxies with inconspicuous spiral structures are found in the M 81 group (NGC 4236 and IC 2574).

Unlike the number density of young stars, the number density of red giants does not increase in the region of the hypothetical ring or spiral arms (Fig. 4a). This is consistent with the hypothesis that the galaxy may have a spiral structure, since the spiral galaxy NGC 300 shows a similar red-giant distribution un-correlated with the locations of spiral arms [31].

Field S5, which is located at a greater galactocentric distance, has been imaged only in a single filter. We nevertheless analyzed the distribution of stars in this field. Since this region may contain only foreground stars and red giants of NGC 2366, we obtained a list of stars consisting mostly of red giants by selecting on the luminosity function for the S5 stars the luminosity interval between the boundary of the tip of the red-giant branch and the photometric limit with 50% sample completeness (based on photometry of artificial stars). The distribution of the number density of stars selected in this way shows a monotonic density decrease with radius (Fig. 4f), without any obvious change in the gradient. The very small extrapolation of the distribution of stars of this field to zero number density indicates the nearness of the thick-disk boundary.

We drew the final boundaries between the stellar subsystems (thin and thick disks) based on our analysis of the distributions of the stars in all the fields studied. We proceeded from the assumption that the stellar disks are symmetric. Images of new fields can alter the locations of the boundaries only slightly. This conclusion is corroborated by a recently found single image taken with the ACS/WFC camera of the HST telescope in the R filter near field S7. This image confirms the correctness of the thick-disk boundary drawn in this paper.

The distribution of red giants with galactocentric radius in the field S7, located far from the center of the galaxy (Fig. 4j), shows a well-defined change in the number-density gradient at a galactocentric distance of 6.1 kpc. We conclude, by analogy with the distributions of stars in spiral and irregular galaxies [6, 9, 31], that the observed break in the distribution of the red-giant number density coincides with the boundary between the thick disk and halo. We verified this hypothesis by constructing the distribution of stellar number density in this field perpendicular to

the radial direction (Fig. 4i). The distribution of stars in this direction shows no gradient, as we would expect if the stars in field S7 form a disk structure (thick disk and halo) that is symmetric about the center of NGC 2366.

The distribution of red giants in field S6, which is the farthest from the center (Figs. 4g, 4h), shows no obvious radial variations of the stellar number density. This seems to indicate either a lack of stars of NGC 2366 in this field or very small gradients of the decrease of the number density of halo stars. In any case, to improve the results, photometry of stars in larger areas of the galactic halo and longer exposures are required to increase the number of halo stars involved.

FOREGROUND STARS.

The effect of foreground stars on our results is significant only for the small statistical sample of red giants we have studied. This effect should show up when analyzing stars in the halo, which has a low stellar density. To approximately estimate the effect of foreground stars, we analyzed HST images of areas with Galactic latitudes close to that of NGC 2366 [32]. The results suggest that the number of foreground stars is insignificant, and that these stars form no clumps in the CM diagrams. At the same time, despite their spatially tenuous distribution and the presence of significant photometric errors due to their faintness, stars in the galaxy periphery do form clumps in the CM diagrams that are concentrated toward the RGB.

Since NGC 2366 is located fairly far from the equatorial plane of our own Galaxy ($b = 28.5^\circ$ for NGC 2366), the effect of foreground stars should be negligible. An analysis of the CM diagram of the field S6, which is farthest from the galactic center, shows that, even if they are present, RGB stars in this field are very sparse, despite the long exposures used to take the images in this field (Table 2). We can therefore treat, with appropriate caution, our results for this field as the results for a foreground field in the close vicinity of NGC 2366.

RESULTS AND DISCUSSION.

(1) Our stellar photometry in several fields of the galaxy NGC 2366 has enabled us to refine the distance to this galaxy. Our new distance estimate, $D = 3.13 \pm 0.25$ Mpc, agrees with that of Karachentsev et al. [27], but differs significantly from estimate of Thuan and Izotov[26].

(2) Our analysis of the visible distributions of stars of various ages has revealed the thin disk, thick disk, and halo stellar subsystems in NGC 2366.

(3) We have determined the sizes of the thin and thick disks along several directions from the center of the galaxy, as well as the boundaries of these subsystems assuming symmetry of the stellar disks (Fig. 1). We find the thicknesses of the thin and thick disks in the Z direction to be 4 and 8 kpc, respectively.

(4) Based on our results for the distribution of young stars, we interpret the HI bridges visible in the galaxy HI image as weak spiral arms, and suggest that NGC 2366 is a low-mass spiral galaxy.

(5) Our results for the distribution of red giants in the field S7 suggest the existence of a halo in NGC 2366. However, further observations of larger fields with deeper photometric limits are needed to confirm this conclusion, and to determine the size of the halo.

The sizes of the stellar subsystems in NGC 2366 that we have obtained are not consistent with the average sizes for subsystems in irregular galaxies [6, 9], but agree better with the sizes of subsystems in spiral galaxies [31], lending indirect support for the hypothesis that NGC 2366 is a spiral galaxy. We showed earlier, based on similarities of their stellar structures, that subdividing galaxies into spirals and irregulars can be fairly arbitrary, and that both classes of galaxies are more correctly called disk galaxies. Our analysis of the distribution of stars in NGC 2366 demonstrates again an absence of differences in morphology between the stellar structure of spiral and irregular galaxies.

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Table 1: Basic data for NGC 2366

R.A.(2000.0)	DEC.(2000.0)	V_h	B_t^0	Type	A_v	A_i	i	$m - M$	M_B
$07^h28^m54.^s66$	$+69^\circ12'56.''8$	100	10.95	IB(s)m	0.120	0.070	90.0	27.48	-16.53

The V_h and B_t^0 magnitudes and thr galaxy type are adopted from the NED database.

The extinction coefficients are adopted from [13].

The inclination of the galaxy i is adopted from the LEDA database.

The distance modulus ($m - M$) and absolute magnitude M_B are determited in this paper.

Table 2: Log of archive data of WFPC2(HST).

Region	Date of observation	Filter	Galactocentric distance (arcmin)	Exposure	Number of HST proposal	Number of stars on the CM diagram
S1	2000-09-18	F814w	0.72	600	8601	11403
	2000-09-18	F606w	0.72	600	8601	
S2	2000-12-12	F814w	1.20	4100	8769	17165
	2000-12-11	F555w	1.20	6700	8769	
S3	2002-01-08	F814w	3.42	2×1000	9318	6008
	2002-01-08	F606w	3.42	2×700	9318	
S4	2001-12-29	F814w	3.66	2×1000	9318	2853
	2001-12-29	F450w	3.66	2×1000	9318	
S5	1999-07-27	F606w	7.00	2×500	8090	—
	1999-07-27	F606w	7.00	2×1000	8090	
	1999-07-27	F606w	7.00	2×1200	8090	
	1999-07-27	F606w	7.00	2×1500	8090	
S6	1996-04-19	F814w	10.03	3400	5971	450
	1996-04-19	F606w	10.03	7900	5971	
S7	1996-12-07	F814w	6.54	15000	6802	1648
	1996-12-07	F606w	6.54	4200	6802	

Table 3: Published distance-modulus estimates for NGC 2366.

Distance modulus	Method	Reference
27.07	blue supergiants	[13]
27.10	blue supergiants	[32]
27.62	blue supergiants	[14]
27.68	Cepheids	[16]
27.67	red supergiants	[26]
27.52	red supergiants	[25]

Our distance modulus estimate is $(m - M) = 27.48$

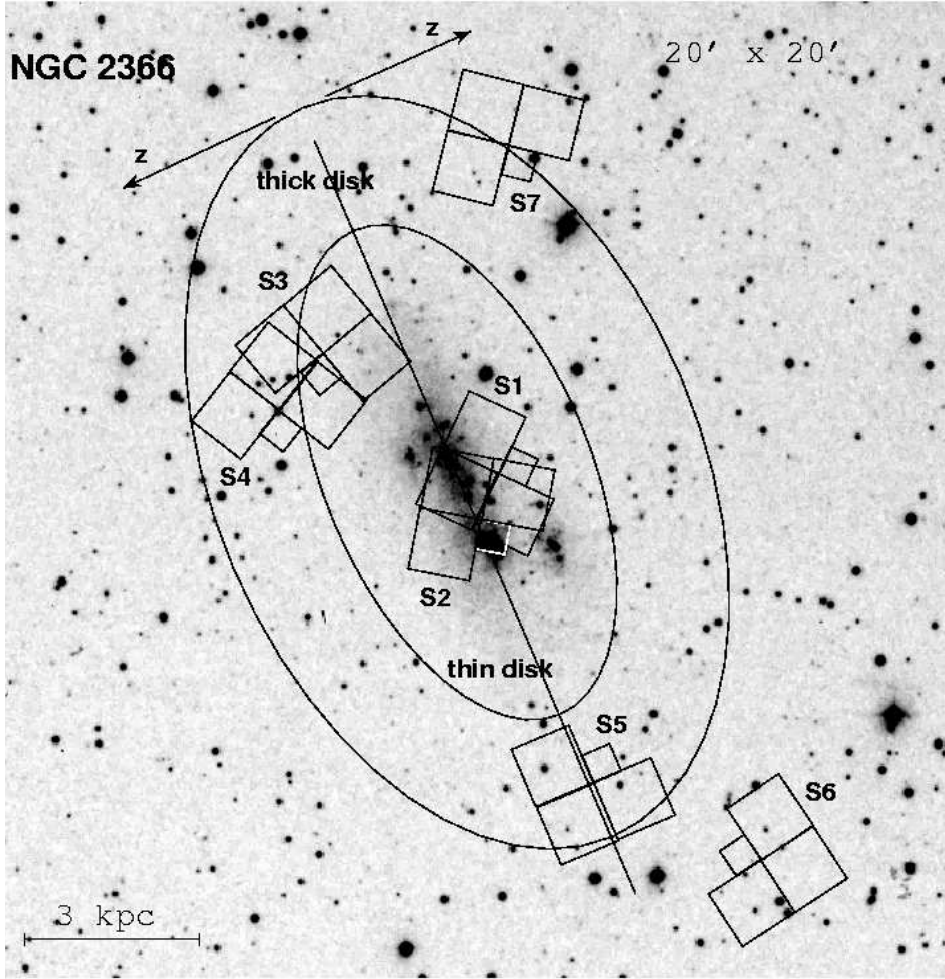


Figure 1: Image of NGC 2366 adopted from the DSS-2 survey. The studied areas, imaged with HST/WFPC2, and the directions Z along which the distribution of stellar number density was analyzed are shown. The inner ellipse delimits the thin-disk region. The outer ellipse corresponds to the boundary between the thick disk and halo.

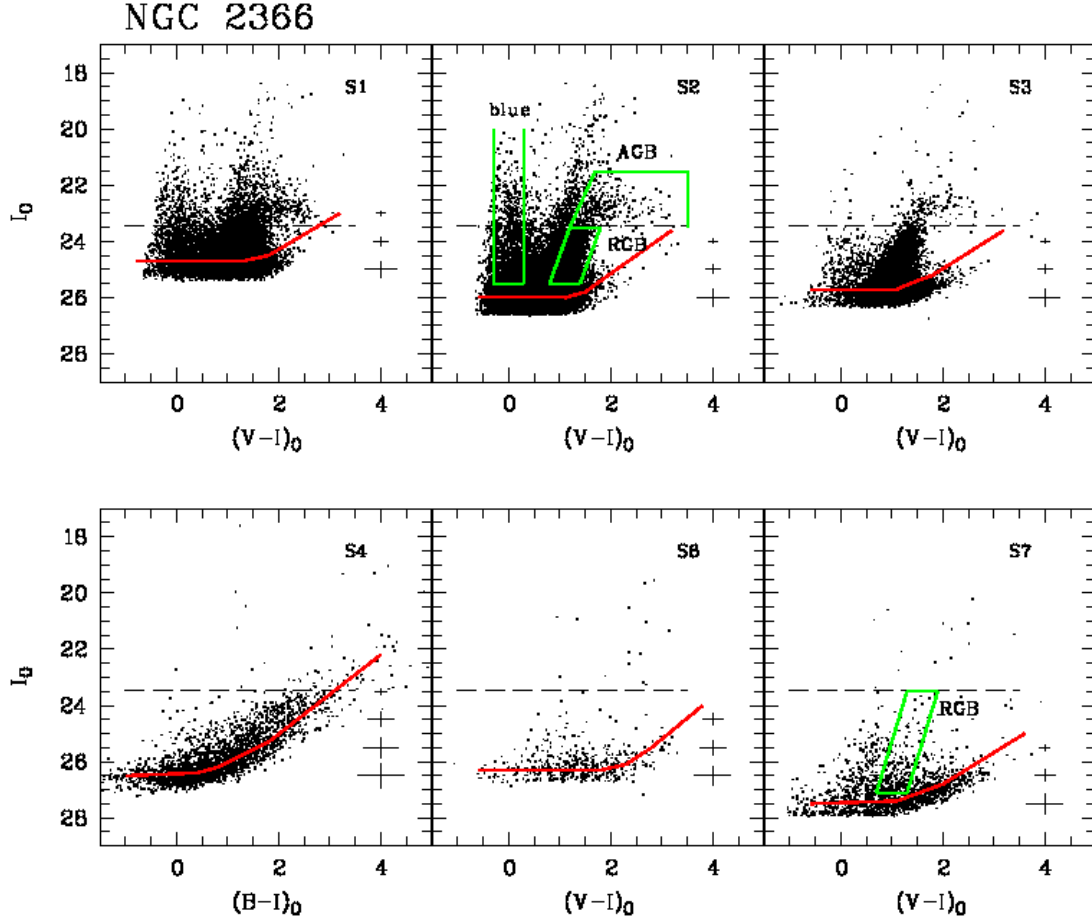


Figure 2: Color-magnitude diagrams for the fields studied (S1, S2, S3, S4, S6, S7) in NGC 2366. The dashed lines show the extinction-corrected position of $I_{RGB}^0 = 23.^m47$ and the solid line the 50% completeness level for the stellar sample determined using an artificial-stars test. The photometric error boxes are shown. The domains of stars of various ages are shown in diagrams for areas S2 and S7: young blue stars (blue), intermediate-age stars (AGB), and old stars (RGB).

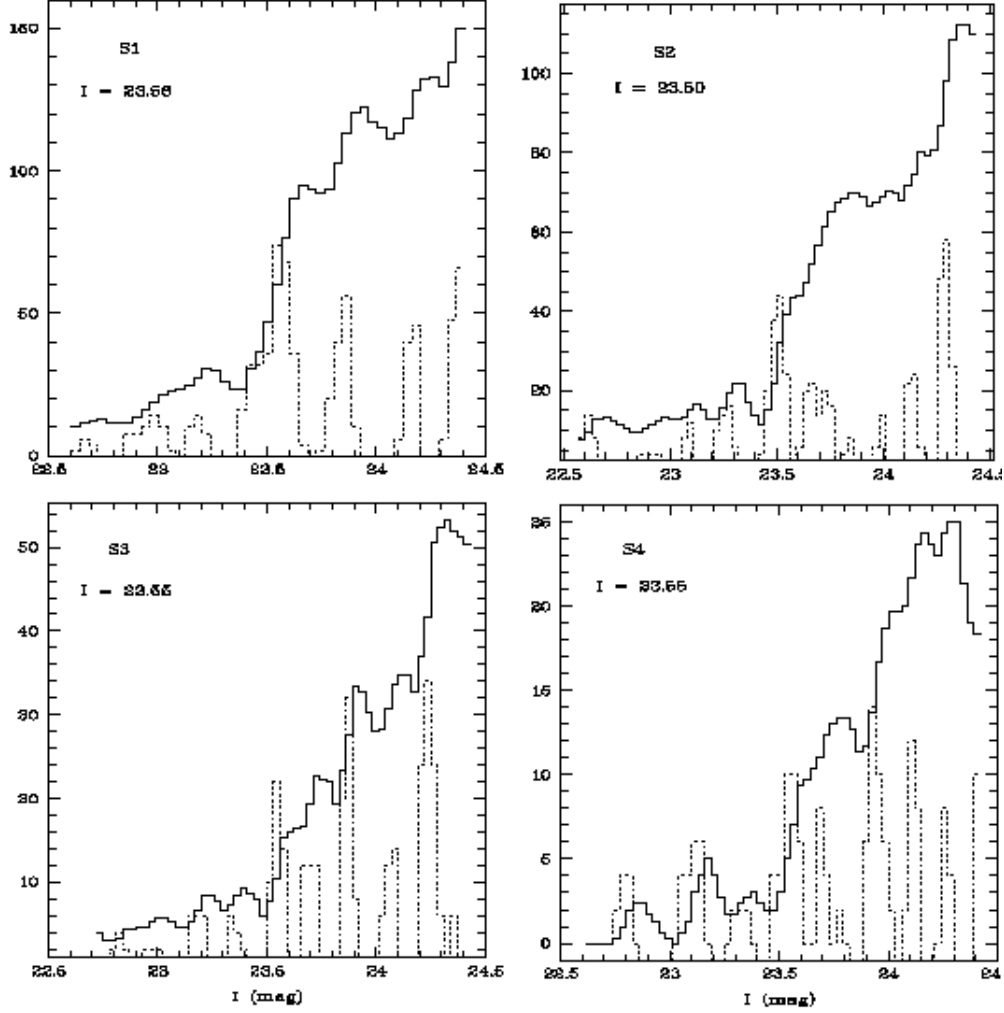


Figure 3: I -band luminosity functions for $(V - I > 1.0)$ stars in the fields studied (S1, S2, S3, S4). The abrupt change in the number of stars corresponds to the start of the red-giant branch, which is used in the TRGB distance-determination method [28].

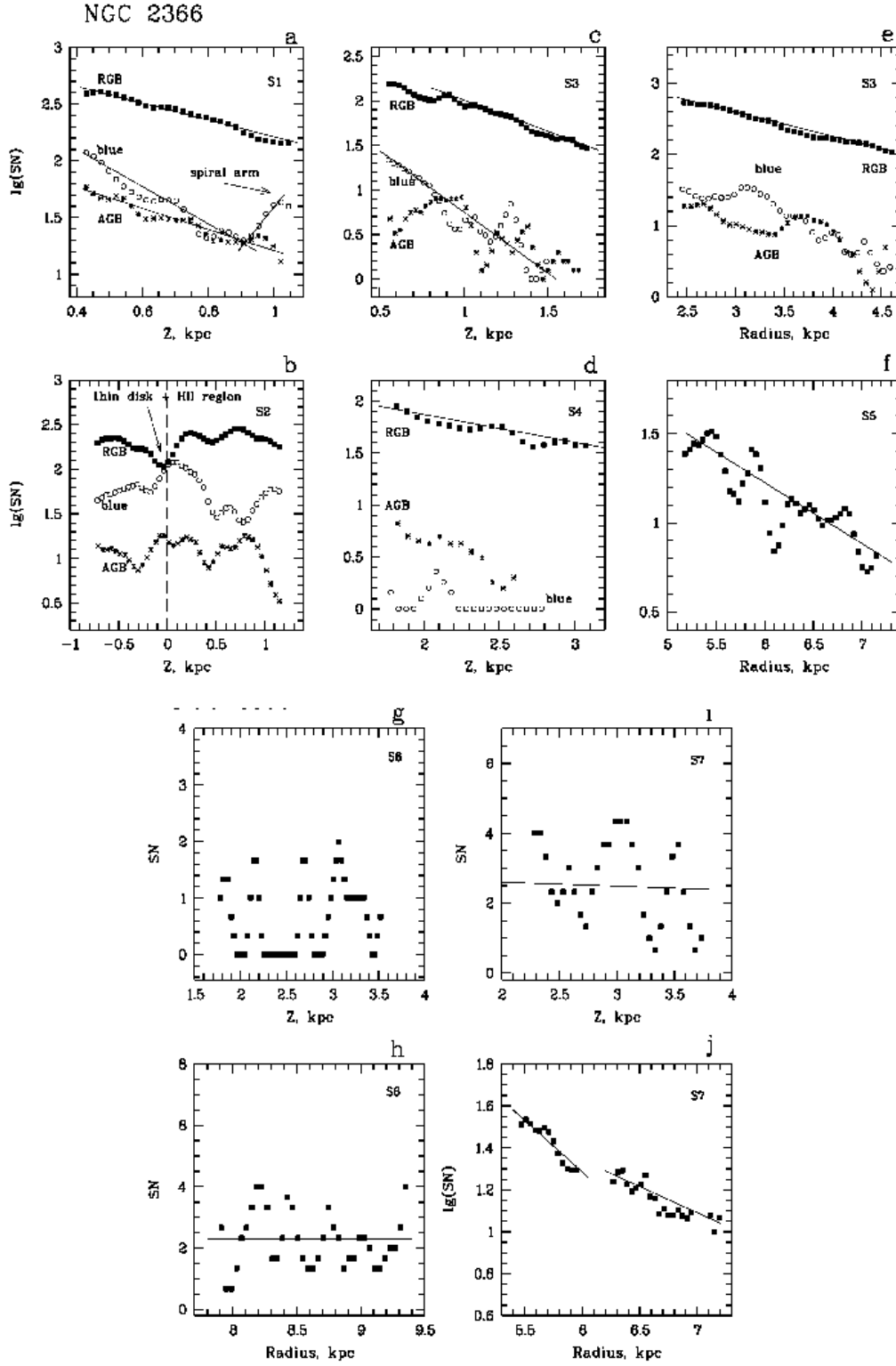


Figure 4: Distribution of the number density N of stars of various types in the NGC 2366 fields studied (S1, S2, S3, S4, S5, S6, S7) along the Z axis and the radial direction R . The Filled squares, open circles, and asterisks show red giants (RGB), blue stars, and AGB stars, respectively.